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RADIO FACSIMILE
VOLUME I: FINAL REPORT

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FOREWORD

Among the responsibilities assigned to the Office of the Manager, National Communications System, is the management of the Federal Telecommunication Standards Program. Under this program, the NCS, with the assistance of the Federal Telecommunication Standards Committee identifies, develops, and coordinates proposed Federal Standards which either contribute to the interoperability of functionally similar Federal telecommunication systems or to the achievement of a compatible and efficient interface between computer and telecommunication systems. In developing and coordinating these standards, a considerable amount of effort is expended in initiating and pursuing joint standards development efforts with appropriate technical committees of the Electronics Industries Association, the American National Standards Institute, the International Organization for Standardization, and the International Telegraph and Telephone Consultative Committee of the International Telecommunication Union. This Technical Information Bulletin presents an overview of an effort which is contributing to the development of compatible Federal, national, and international standards in the area of facsimile. It has been prepared to inform interested Federal activities of the progress of these efforts. Any comments, inputs or statements of requirements which could assist in the advancement of this work are welcome and should be addressed to:

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Final Report

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1. EXECUTIVE SUMMARY

This project deals with the possibility of transmitting FAX over radio voice-channels using existing FAX machines and existing radio installations. No modification or retrofit to FAX machines or radios is considered; however, additional equipment in the form of an interface adapter or modem is allowed.

The investigation is primarily concerned with the use of HF radio. This is due to the long-range communication which HF provides. In addition, HF channels present the greatest problems in transmission of FAX signals. VHF and UHF radios present less difficulties. These radios are often used in combination with wire-lines and are sometimes considered part of the wireline channel. This is often the case with mobile radio.

Group -1, -2, and -3 FAX are tested on simulated HF channels using the Government's HF simulator at Ft. Monmouth, N.J. The major degradations for which tests are run include: thermal noise, man-made noise, flat fading, selective fading, and frequency translation. Composite tests, including a number of these degradations, are also made. Volume II of this report includes the actual test results.

The FAX machine used for the tests is the Panafax PX100.

Tests include both the premessage exchange and the message portion of the FAX transmission.

Test results show that the wire-line modem used for Group-3 FAX does not work well on HF channels and that the minimum data rate of 2400 bps is too high. This results in failure of transmission for Group-3. Group-2 FAX also fails for a number of simulated channels.

Group-1 FAX produces documents on most simulated channels even though the quality of the document degrades as the impairments become severe; however, the degraded document can be considered usable in most cases.

Results indicate two possibilities for attaining long-range HF-radio FAX. The first is to use group-1 FAX and to accept the six-minute transmission time. This approach requires only an interface adapter to convert the two-wire FAX signal to the four-wire radio signal and to generate the push-to-talk control.

A second approach is to use group-3 FAX in a digital mode with an external modem designed for operation via HF radio.

Transmission time using group-3 FAX in this mode will be sacrificed since it is likely that the HF modem will work at rates of 2400 bps or less.

2. INTRODUCTION

Most high-performance FAX equipment is designed for use on telephone channels. Recently there has been considerable interest in the possibility of transmitting FAX via radio using existing FAX equipment. This interest stems from two distinct sources. The first involves a need by some Government activities to employ radio-FAX in the normal course of operations. The second involves the need to transmit FAX via the emergency communication network.

In both cases the medium of primary interest is long-haul high-frequency radio, HF; however, for non-emergency communications radio FAX using VHF or UHF may also be of interest.

The telephone plant is highly vulnerable to enemy attack. Microwave links including satellites are particularly vulnerable. For this reason, an emergency communications network based on high frequency or HF radio is planned (SHARES).

An HF radio channel is established by virtue of the refractive properties of the ionosphere. Communication over great distances is possible with only a rudimentary radio installation and a minimum of transmitter power. During an initial attack, HF communications may be disrupted by

disturbances in the ionosphere; however, the ionosphere will return to normal and communication can proceed.

Unfortunately, the channel capacity of a typical HF link is much less than that of a telephone channel. Even though both channels might be usable for voice, the quality of the HF channel is often considered poor. This poor quality is partly due to thermal and impulse noise, and partly due to fluctuations in the ionosphere which cause dynamic perturbations in the channel transfer-characteristic. A great deal of effort has been spent in overcoming these degradations, especially for data transmission via HF [1]. Even so, the accepted data rate for HF is taken to be a maximum of 2400 bps, while for telephone, the rate is 9600 bps. With these facts in mind, a question arises concerning the rate and quality for which facsimile transmission on HF and other radio channels might be possible. A companion question concerns the possibility of using existing wire-line FAX equipment on radio channels. The present study is aimed at providing answers to these questions.

3. BACKGROUND

In order to deal with the problem of evaluating the performance of several different FAX signals with a number of different radio circuits it is necessary to define both FAX equipment and radio channels. It is also helpful to have in mind the basic characteristics of each. This information is useful in developing a test plan according to certain ground rules as described in the following paragraphs. The plan is aimed at measuring performance rather than interpreting or evaluating results.

When dealing with such a large number of combinations of equipments and conditions, it is essential that the test plan be well defined and limited; otherwise, the tests may easily expand to an intractable number. A single page of group-1 FAX requires six minutes of simulator time. Set-up and premessage testing requires considerably more.

3.1 FAX Equipment

The three types of FAX equipment tested are defined according to CCITT standards. These are groups-1, -2, and -3. The signal for group-1 is frequency-shift keying, FSK. For group-2 the signal is vestigal sideband, VSB; and for group-3 the signal is differentially-coherent phase-shift keying DCPSK. For group-1 and -2 the signal is continuous in time; thus, these are referred to as analog FAX. For group-3 the signal is quantized

in time; hence, group-3 is referred to as digital FAX.

Group-3 equipment contains a wire-line modem with an automatic adaptive equalizer. This type of modem performs well on wire-lines and is often used for bit-rates up to 9600 bps. Unfortunately these modems are designed to track slowly varying changes such as those encountered in the wireline transfer characteristic. Such modems may be expected to have trouble tracking the rapid fluctuations in the transfer characteristic of an HF radio circuit.

In addition to document transmission, each group employs a premessage exchange consisting of tonal signaling. The group-3 premessage exchange also contains a training sequence for the equalizer. If the premessage exchange fails, the document transmission generally does not start. In the case of group-3, a document which has started can be cut off if the transmission results in too many errors.

3.2 Radio Circuits

The radio circuits considered are assumed to be those circuits presently being used for voice communication. These voice circuits are further divided into three types depending on radio frequency. The types are: high frequency (HF), very high frequency (VHF), and ultra high frequency (UHF). When used in combination with a FAX machine, the radio circuit is considered a

voice channel having a transfer characteristic and signal-to-noise ratio determined by the radios and medium employed.

HF radios employ single-sideband modulation exclusively, while VHF and UHF radios generally employ frequency modulation. The single-sideband modulation and the characteristics of the HF medium are the main factors in determining the characteristics of the audio channel for HF radios.

Unless otherwise specified, the HF radio circuit will be considered a skywave or long-haul circuit. The ground-wave or short-haul circuit will be discussed in later sections.

The equivalent audio channel for HF radio is quite different from its wire-line counterpart. The wire-line channel is characterized by low noise and relatively stable amplitude and phase distortion. Frequency translation on wire-lines is low, typically ± 5 Hz.

The equivalent HF radio channel is characterized by poor signal-to-noise, a rapidly fluctuating transfer characteristic and a relatively large frequency translation of ± 75 Hz. Natural and man-made interference as well as adjacent channel interference are common on HF radio circuits.

The maximum data rate for long-haul HF radio is taken by

modern standards to be 2400 bps. For wire-lines 9600 bps is common.

UHF and VHF radio circuits using FM radios have audio channels more nearly equivalent to wire line channels. The signal-to-noise ratio is better than that for HF circuits and the transfer characteristic is better even than that for many wire line circuits. The disadvantage of the circuit is that communication range is limited to slightly beyond the horizon (for terrestrial antennae and under normal atmospheric conditions).

Over-the-horizon communication for mobiles is often achieved by using UHF or VHF radio circuits in combination with wire-lines (including microwave). In these cases, the FM radio links do not add significantly to the wire-line characteristic and the overall audio channel is considered a wire-line channel. Even though such a channel terminates in radio equipment, the total channel is just as vulnerable to attack as is the telephone plant.

3.3 Emphasis and Ground Rules

Present emphasis is placed on transmission of FAX via long haul HF radio. Although the long-haul HF channel is the poorest audio channel presently in use, it is also the least vulnerable to attack. Furthermore, a considerable body of knowledge exists

concerning the impairments of the channel and methods of combatting these impairments. The recent modem tests at Ft. Huachuca illustrates the present work being done to provide reliable long-haul HF data communications [1].

Only presently available equipment, installed and in use, is considered in this study. No consideration is given to the possibility of modifying FAX machines nor to modifying radio installations. It is assumed that the radio installation provides a satisfactory voice channel and it is this channel over which transmission of FAX is evaluated.

One addition to the FAX equipment may be necessary. This is an interface adapter to convert the FAX machines and radio equipment. The necessity comes about because the wire-line FAX machine has a 2-wire interface while radios generally have a 4-wire interface. Thus, the necessary interface equipment is a 2-wire to 4-wire adapter. This can be a hybrid transformer similar to that used in the telephone hand-set or a circuit performing a similar function.

3.4 Approach to Testing

Evaluation of a particular FAX equipment, such as group-1, -2, or -3 on a particular HF channel can be done analytically to some extent; however, without detailed knowledge of the design of the FAX equipment it is impossible to get more than a qualitative

answer. For this reason the three types of FAX equipment being considered are tested in real-time using an HF channel simulator. The simulations are performed using the Governments Signation S250A simulator at Ft. Monmouth N. J. under the direction of Mr. John Jeski.

In this way the channel degradations are tightly specified and the quality of the FAX transmission is related to a specific channel degradation. Combined degradations are also simulated although not to the same extent as the single degradations, the philosophy being that if a transmission fails for a single degradation it will certainly fail if additional degradations are added.

Most of the testing done with combined degradations was done using values of the degradations which of themselves did not cause failures.

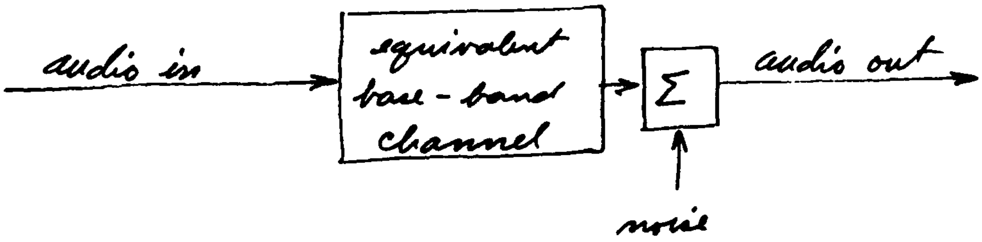
No field testing was done in the present study. The characteristics of an HF channel vary so widely with time of day and season of the year that obtaining a channel exhibiting a particular degradation becomes very difficult. Furthermore, some sounding method is necessary to determine what sort of channel actually exists. Although field testing is valuable in verifying equipment design it is best used to substantiate simulations and not as a substitute. For these reasons, and because of the time and expense involved, field testing was not employed in the present study.

4. THE BASE-BAND HF CHANNEL

Figure 4.1 illustrates the concept of an equivalent base-band channel. Part (a) of the figure illustrates an actual HF link consisting of SSB transmitter and receiver, antenna and the medium. The audio signal enters the transmitter, is translated to RF, is transmitted over the medium, enters the receiver corrupted with noise, is translated down to audio, and leaves the receiver. The fact that the modulation is single sideband is not significant except as pertains to translation error.

The equivalent base-band channel is illustrated in part (b) of the figure. Here the translations to and from RF are neglected; otherwise, the equivalent base-band channel is assumed to contain the same transfer characteristic as all the elements of part (a) combined. That is, the frequency characteristic of the equivalent channel is the product of the frequency characteristic of transmitter, receiver, and medium. In addition, the equivalent channel is assumed to contain a frequency translation equal to the translation error between transmitter and receiver. The channel noise is added at the receiver as shown in part (b) of the figure. This is the equivalent base-band channel simulated in all tests described in the following paragraphs.

(a) an HF radio link



(b) equivalent base-band channel

Figure 4.1 The Base-Band HF Channel

4.1 Dynamic Nature of the HF Channel

Unfortunately, the equivalent base-band channel cannot be considered time-invariant because of multipath transmission, typical of the HF links. The phenomena of multipath is quite complex; however one simple example will show the way in which it occurs and illustrate the time dependence. Figure 4.2 shows a sky wave reflected by two different layers of the ionosphere. This causes the two waves to reach the receiver at slightly different times thus producing cancellation and reinforcement as a function of frequency. Since the layers of the ionosphere are continuously moving relative to each other, the differential delay at the receiver will also be changing continuously. This results in a change in frequencies of cancellation and reinforcement, thus producing a dynamically varying frequency characteristic. This phenomena is described in more detail in Appendix A.

4.2 HF Channel Parameters

In order to address the question of whether or not FAX can be transmitted over voice-grade HF channels, the channel parameters must be defined. This is a difficult task since some parameters such as frequency translation may be quite detrimental to transmission of FAX, but only slightly detrimental to speech. From the literature and from conversations with users, the parameters listed in Table 4.1 are taken as typical of a

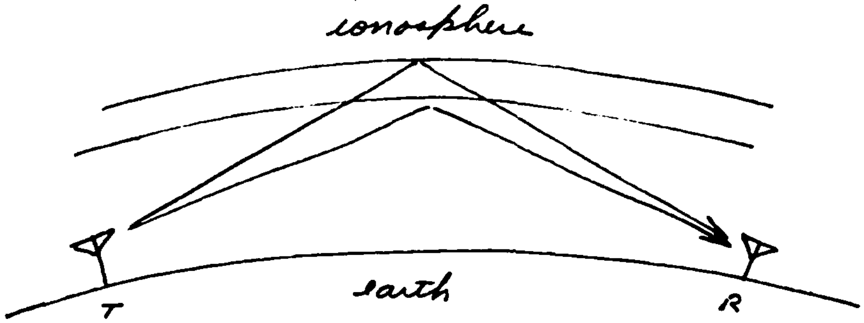


Figure 4.2 Example of Multipath

S/N	-	10 dB.
Impulse Noise	-	500/min (depends on receiver location).
Multipath	-	secondary paths 3 dB down.
Flat fading	-	Doppler spread equals one Hz.
Doppler shift	-	$\pm$ 75 Hz for older radio's, less for new equipment

Table 4.1 - Typical Impairments on a Good HF Voice Channel

voice-grade HF channel. The parameters are listed in a way corresponding to the settings of the Signation simulator.

The first parameter is signal-to-noise ratio in the audio band. There seems to be general agreement that a 10dB ratio is a "good" HF channel.

The second parameter is man-made impulse noise which occurs when a receiver is located in a populated area with electrical machines. There seems to be little agreement on a typical parameter; however the rate of 500/min seems to be an acceptable test parameter.

Multipath propagation is one of the most severe impairments to the transmission of FAX. The worst case occurs with two paths of equal magnitude which results in complete cancellation at some frequencies. The specification of a 3dB path difference is a compromise which seems to be fairly typical of HF channels.

Flat Rayleigh fading is that type of fading so noticeable in HF voice channels. In the case of a voice channel, the result appears to be a rising and falling signal strength. To some extent this type of fading is a test of the AGC in the system. The Doppler spread which determines the rate-of-fade is typically one Hz.

The so called Doppler shift is really a frequency translation in the received audio. This occurs due to the fact that the SSB transmitter and receiver have oscillators which are

slightly off frequency. Although there is a slight Doppler shift due to the medium, it is rather small compared to that due to the radios. The worst-case Doppler shift for older radios is specified to be ±75 Hz. For newer radios the Doppler shift is significantly reduced.

5.0 TESTING ON SIMULATED HF CHANNELS

Testing on simulated HF channels was performed using the Government's HF simulator at Ft. Monmouth, N.J. The simulator is a Signatron S250A. Tests were performed under the direction of Mr. John Jeski.

5.1 Test Arrangement

The test arrangement used for testing on simulated channels is illustrated in Figure 5.1. The FAX machines are Panafax PX100's. These machines can be set to operate as group-1, group-2 or group-3 equipment. This setting was used during the course of the tests to select the group-equipment being tested. When operating as group-3 equipment, the maximum data rate can also be selected by a switch setting. This selection was also used during the tests to select either a 2400 bps or 4800 bps data rate.

Normally the Panafax machine provides a two-wire interface to wire-line channels. For test purposes, the machines were temporarily modified to provide a four-wire interface as shown in the figure. This is not considered a modification to the machines since the same result could have been achieved with an external interface adapter.

Referring again to Figure 5.1, a manual switch is provided to by-pass the simulator. This switch is used in cases where the

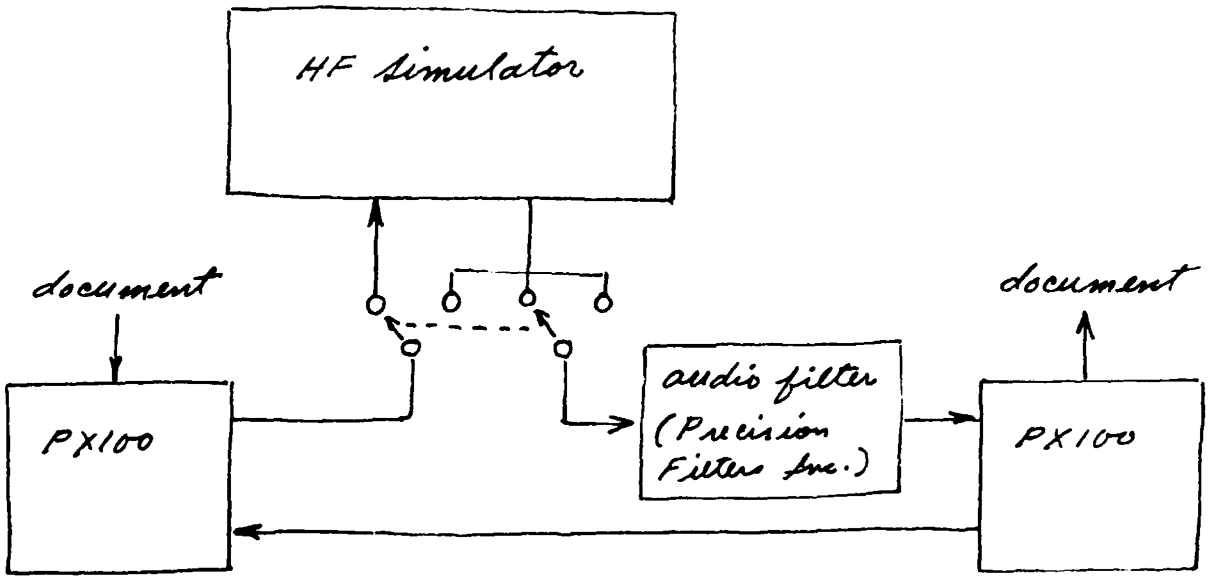


Figure 5.1 Test Arrangement Using HF Simulator

premessage exchange fails and yet it is desired to see a received document. In these cases the premessage exchange is transmitted with the simulator by-passed. When the document starts the simulator is thrown in by means of the switch. Data from the tests show a few such cases. The point in the received document where the switch is thrown is usually obvious.

The simulator at Ft. Monmouth has a bandwidth of 12 kHz. In order to ensure that reception is not benefiting from a bandwidth greater than that of the base-band audio channel, an audio filter is used between simulator and the receiving FAX machine. This filter is set to give a bandwidth from 600 to 2800 Hz. This results in an actual signal-to-noise ratio at the receiver which is 7.5 dB higher than the simulator setting.

The simulator is always set for a base-band simulation.

All connections in Figure 5.1 are terminated in 600 ohms.

5.2 Test Results

All test data taken using simulated HF channels is presented in Volume II. This includes: a base-line test with no impairments to ensure that the test equipment is working; a series of tests for single impairments; and a few tests for multiple impairments. Major emphasis is placed on the single-impairment tests since these provide the most insight into the cause of any deterioration in quality of the received document.

When performing a set of tests it is somewhat difficult to know at what level of impairment to start. Furthermore time limitations prevent exhaustive testing especially since three groups must be tested both for premessage exchange and for the message portion of the transmission. In general, parameters are selected to include those of the voice-grade HF channel and tests are made about this point. In some cases this results in too much data and in others one might wish for more. In any case, all data is presented in Volume II. The salient features are summarized in the following paragraphs.

5.2.1. Gaussian Noise

Tests II-A-1 through II-A-5 of Volume II illustrate performance in the presence of Gaussian noise. These test results are summarized in Table 5.1.

At a signal-to-noise ratio of 10 dB, which is considered a good signal-to-noise ratio for a voice-grade HF channel, group-1 and group-3 failed to start a document consistently. Group-2 started documents but the quality was unacceptable.

At a signal-to-noise ratio of 16 dB all groups gave good documents; but group-3 still failed to start occasionally. This failure of group-3 to start still persisted at 22 dB signal-to-noise ratio.

signal-to-noise ratio	group-1	group-2	group-3
10 dB	fails	poor document	fails
16 dB	good document	good document	fails (good document)
22 dB	good document	good document	good document (fails occasionally)

TABLE 5.1 RESULTS OF TESTS USING GAUSSIAN NOISE

These tests show that the wire-line FAX equipment is not designed to handle the high levels of noise common on HF links. This applies both to premessage exchange and document transmission.

For more detailed data, please see tests II-A of Volume II.

5.2.2 Impulse Noise

Tests were made using three values of impulse noise. The test results are given in tests II-B-1 through II-B-3 of Volume II. In all cases the impulse duration was one millisecond.

The results show that the noise does not have a great effect on group-1 and group-2 FAX, although the impulses are clearly visible in the received document when the peak impulse power is set at 6 dB above signal power.

In the case of group-3 the impulse noise causes a deterioration in the received document. As one would expect, the effect increases as impulse power increases. For 500 impulses/min with peak power 6 dB above signal, the received document is unacceptable.

The data collected for impulse-noise tests illustrate a feature which is exhibited in many of the single-impairment tests

performed. Since group-1 and group-3 do not use data compression; an impairment, such as an impulse, simply causes a perturbation in the area of the document corresponding to the time when the impulse occurred. For group-3, because of the compression algorithm, a bit-error may cause the entire line to be in error; thus causing the apparent deterioration in the document to proceed more rapidly than with group-1 or group-2.

5.2.3 Multipath Propagation

Tests II-C-1 through II-C-9 of Volume II are the tests of performance in the presence of multipath propagation. Test II-C-1 is for the worst case; namely 2 equal paths. This causes complete cancellation of the signal at a set of equally spaced frequencies. The severity of this selective fading is reduced in subsequent tests by alternating the signal in the secondary path.

In all cases of two paths the differential path delay is 1 millisecond. The secondary path is also given a frequency off-set to simulate the dynamic nature of selective fading. The off-set causes the fades to march across the band, the period between fades at a given frequency being equal to the off-set.

The results of the first seven tests, namely those involving two paths, are summarized in Table 5.2. As can be seen from the table, multipath severely degrades the performance of all groups although group-1 seems to suffer the least.

path difference	group-1	group-2	group-3
3 dB	poor document		
6 dB	poor document		fails
9 dB		very poor document (some failure)	poor document (some failure)
12 dB	good document	poor document	good document
15 dB		poor document	
18 dB		fair document	

TABLE 5.2 RESULTS OF MULTIPATH TESTS

A poor document can be obtained using group-1 with only 3 dB difference in the two paths. To get a good document using group-3 requires a 12 dB difference. Group-2 only gives a fair document with 18 dB difference.

Multipath propagation is quite typical of long-hand HF links. This is a form of impairment not normally encountered on wire-line. This is particularly true considering the dynamic nature of multipath fading. One might anticipate that the performance of a wire-line modem, such as a group-3 modem, based on adaptive equalization, would degrade with dynamic multipath fading.

5.2.4 Flat Fading

Test II-D-1 is that for flat fading. Due to time limitations only one value of Doppler spread was used; however, the tests show dramatically that group-2 and group-3 give degraded documents in the presence of flat fading. Only group-1 gives an acceptable document. Furthermore, group-2 failed to start once and group-3 failed to start five times in succession in the presence of flat fading.

5.2.5 Doppler Translation

Performance in the presence of Doppler translation is measured by tests II-E-1 through II-E-6 of Volume II. When testing for translation a question arises as to whether or not the direction of translation makes a difference. In the present instance this did not seem to be the case; however, the 75 Hz translation was made in both directions.

The results show that only group-1 can tolerate the ±75 Hz translation. Group-2 and group-3 give good documents at 32 Hz translation. For the older radios still in the field it is significant that group-1 can take the worst case translation which these radios may induce in a link.

5.2.6 Multiple Impairments

Tests III-C-1 through III-C-4 of Volume II illustrate the performance of each group when multiple impairments are introduced. It is not really practical to run a complete set of tests with multiple impairments because the numbers become so great. The four tests made were selected to contain impairments which by themselves were not catastrophic. The results again show that group-1 produces a somewhat better document than group-2 or group-3 in the multiple impairment situation.

6.0 CONCLUSIONS AND RECOMMENDATIONS

Tests using the HF simulator show, as might be anticipated, that the HF radio circuit does not have the channel capacity of a telephone line. It is not possible to consistently transmit a document over a voice-grade HF radio circuit with the same quality and in the same time frame as can be achieved with wire-line using groups-2 or -3 FAX machines.

Group-2 equipment and group-3 equipment using the internal wire-line modem are not well suited for use with HF radio circuits. The SSB modulation of group-2 seems particularly succeptable to failure due to multipath fading and Doppler error. The automatic adaptive equalizer used in the internal group-3 modem does not work well at the noise levels and with the selective fading common to HF links.

6.1 Group-1 on HF Circuits

Group-1 equipment might be used on some HF circuits when the signal-to-noise ratio is good and multipath not too severe. The effects of channel degradations when using group-1 are to produce a gradual deterioration in the quality of the received document rather than a catastrophic failure. In many cases the received document is still usable even though severely degraded. Group-1 is the most likely candidate for use on HF circuits. Unfortunately the transmission time is 6 minutes per page.

When using group-1 on HF radio circuits, it would be the user's responsibility to obtain the best channel possible. All voice-grade channels are not equally suited for transmission of group-1 FAX.

6.2 Group-3 with External HF-Modem

The modem used for the simulated testing of group-3 FAX is the modem internal to the FAX wireline. This is a wireline modem designed for high data-rates but not designed ot combat the degradation on HF channels. A second possibility which should be investigated for long-haul HF is the use of group-3 equipment with an external HF modem. Although HF modems are expensive, a number are available giving good performance at 2400 bps. Investigation is needed to determine what effect the statistics of the modem errors has on the quality of the received document. (Burst errors may be less detrimental than random errors.) The possibility of obtaining a low-cost modem for radio FAX should also be considered.

6.3 VHF and UHF

It is possible that wire-line FAX equipment would work satisfactorily with VHF and UHF radio circuits. This is particularly interesting to consider when these circuits are part of a longer wire-line link. This possibility should be verified by field experiments.

6.4 Ground Wave HF

A third possibility should be mentioned. This involves the use of short-haul or ground-wave HF circuits. This type of circuit is used by mobiles for communication within a range of about 300 miles [2]. The antenna used are usually "whip" antenna which generate a ground wave. If the sky-wave can be eliminated, this type of circuit is comparable to VHF and UHF circuits except that propagation proceeds further over the horizon. The degradations which occur due to reflection from the ionosphere are absent thus providing a channel closer to that for which the FAX equipment was intended. Of course, one must design the radio circuit carefully to ensure the absence of the sky-wave. Furthermore, this type of circuit does not provide the long-haul capability normally associated with HF.

APPENDIX A - RECEIVED SIGNAL POWER FOR MULTIPATH PROPAGATION

The phenomena of multipath propogation is based on the existence of several individual propoagation paths. The received power in each of these paths may be different. A question now arises concerning the proper figure to use for the resulting signal power at the receiver. One's first reaction would be to add the power in each individual path. On the other hand, since the signals are coherent, there will be bands of frequency where the power is greater than the sum of that in the individual paths, and other bands where the power is less. In fact, for two paths with equal power and finite differential delay, there will be a set of frequencies where complete cancellation occurs at the receiver.

The purpose of this appendix is to analyse multipath propagation in the framework of a filter problem; to show that addition of the power in the individual paths is appropriate; and, in so doing, to highlight some implications of multipath.

Multipath transmission is simulated by adding the signal from two or more individual paths. Associated with each path is a delay and a signal level. For the case of two paths, the equivalent filter is illustrated in Figure A.1. The primary path is assumed to have no delay and the secondary path a differential delay τ. The primary path has a signal level W_1, the secondary path a level W_2.

For the case of equal signal-levels $(W_1 = W_2)$ the corresponding frequency characteristic is shown in Figure A.2. This is the

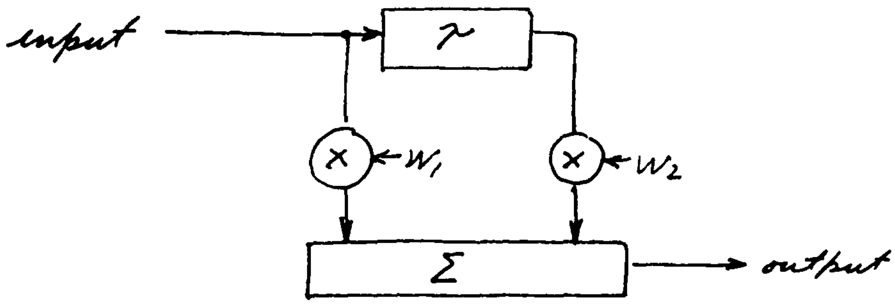


FIGURE A.1: BLOCK DIAGRAM OF MULTIPATH FILTER

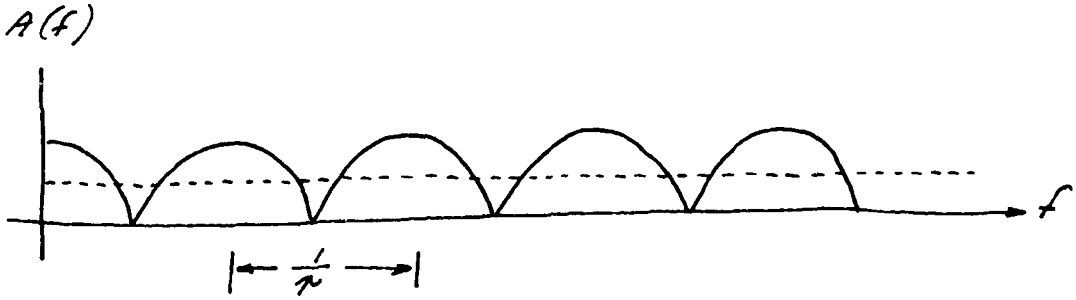


FIGURE A.2: FREQUENCY CHARACTERISTIC FOR EQUAL PATHS

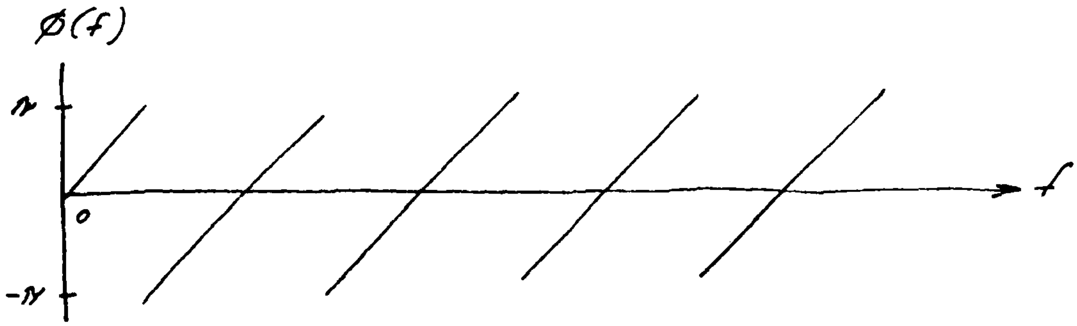


FIGURE A.3: PHASE CHARACTERISTIC FOR EQUAL PATHS

so-called "cosine" filter. The repetition period is $\frac{1}{\tau}$ Hz where τ is the differential delay between the two paths. The dotted line in the figure represents the frequency characteristic of either path alone.

Figure A.3 represents the phase characteristic for the case of two paths with equal signal levels. There is a phase discontinuity at the zeros of the frequency function.

Because of the movement of the various ionospheric layers, the differential delay τ is constantly changing in practical cases. Refering again to Figure A.2, the maxima and minima of the frequency characteristic move to the left as τ increases and to the right as τ decreases. Defining the frequency of the n-th maximum as f_n.

$$f_n = \frac{n}{\tau};\qquad \text{(A.1)}$$

and taking the derivative,

$$\frac{df_n}{d\tau} = \frac{-n}{\tau} = -\frac{f_n}{\tau}\qquad \text{(A.2)}$$

shows that the rate of change of the frequency characteristic with respect to a changing differential delay is directly proportional to the frequency and inversely proportional to τ. The effect of a changing τ in multipath propagation is to cause the maxima and minima of the frequency characteristic to move through the receivers pass-band, the rate of movement being higher at the higher frequencies.

A typical value of τ is 1 m sec; therefore, at a given instant one might find two zeros in a voice-band of 2.4 kHz. As the differential delay becomes smaller one might find only one zero, or none.

Refering now to the question of calculating received signal power, the suggested method is to calculate the average received power over a period of the frequency function, a period being $\frac{1}{\tau}$. This may be viewed as the average power for all frequencies or the time-average for a single frequency if the frequency characteristic is dynamic as just described. A problem occurs only when $\frac{1}{\tau}$ is relatively wide compared to the receiver bandwidth and the rate of change of τ is quite small. Here the average received signal power may be realized only over a long period of time.

Figure A.4 is a vector diagram illustrating the addition of two signals S_1 and S_2 having the same frequency but at phase angle ϕ. The square of the resultant vector, S_r^2 is given by;

$$S_r^2 = S_1^2 + S_2^2 + \int_0^{\pi} 2 S_1 S_2 \cos\phi \, d\phi \qquad \text{(A.3)}$$

The mean value of S_r^2 over a period of the frequency function is;

$$\overline{S_r}^2 = S_1^2 + S_2^2 + \int_0^{\pi} 2 S_1 S_2 \cos\phi \, d\phi \qquad \text{(A.4)}$$

Evaluating (A.4) yields;

$$\overline{S_r}^2 = S_1^2 + S_2^2 \qquad \text{(A.5)}$$

Since power is proportional to the square of the signal, equation

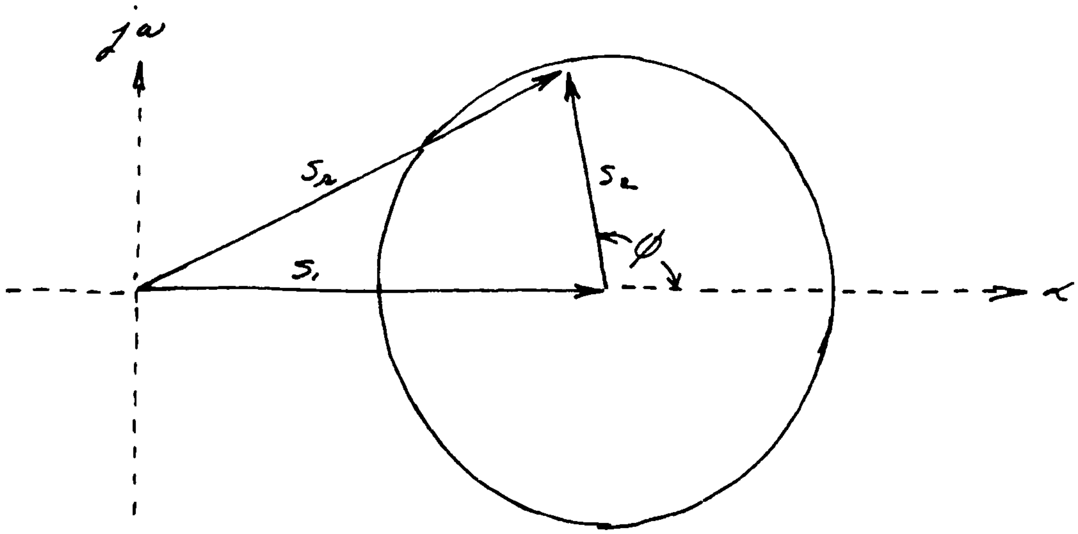


FIGURE A.4: VECTOR DIAGRAM FOR ADDITION OF TWO VECTORS

(A.5) shows that it is proper to add the power in the individual singal paths to obtain the average signal power. Assuming the bandwidth of the receiver is wide enough to accommodate the transmitted signal, equation (A.5) yields the average received power.

When using the Signation S250A simulator, the noise power occupies a 12kHz bandwidth. To obtain the noise power for the receiver requires multiplying the setting on the simulator by the receiver's bandwidth divided by 12 kHz. The complete expression for signal-to-noise ratio at the receiver is;

$$\frac{S}{N} = \frac{\sum_{m=1}^{M} S_m}{\frac{B_n}{12} N_{12}} \qquad \text{(A.6)}$$

where; $\frac{S}{N}$ is the signal-to-noise power, S_m is the power in the m-th path, B_n is the receivers bandwidth and N_{12} is the noise power for the simulator setting.

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[1] HF Modem Comparison Test Report, May 1986; Joint Tactical Command Control and Communications Agency; Joint Test Element; Fort Huachuca, Arizona Coordinated by Mr. Gail Query, Project Coordinator.

[2] Picquenard, Armel; Radio Wave Propagation, Philips Technical Library, Wiley, 1974.

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